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EXTENDING THE MASS RANGE OF THE FERMILAB ENERGY DOUBLER BY COLLIDING 1 TEV "ANTIQUARKS" ON HEAVY NUCLEI

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Abstract

Dorfan et al.[1] demonstrated experimentally that one can extend the mass range of an accelerator by using the Fermi-motion of nucleons inside heavy nuclear targets. The development of antiproton sources and intense pion beams at Fermilab and CERN makes possible a dramatic enhancement of this mechanism. We show that the increase in threshold production using anti-protons or pions rather than protons far exceeds the loss in luminosity.

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Several experiments[1] have demonstrated that the mass range accessible to an accelerator can be extended by exploiting the Fermi-motion of nucleons inside heavy nuclear targets. At higher energies (e.g., Fermilab's Energy Doubler) this mechanism can be dramatically enhanced by using secondary π^+ or $\bar{p}$ beams rather than the direct p beam. In this paper we attempt to assess the significance of this enhanced mechanism for experiments on the Energy Doubler; we will

(i) review the physics of high-mass threshold production;

(ii) demonstrate the advantage of beams containing valence anti-quarks;

(iii) discuss specific physics examples: excitation of weak bosons and new quark flavors;

(iv) point out some experimental possibilities.

In the experiments of Ref. 1 (see Fig. 1), antiprotons were produced by colliding a 3 GeV proton beam with a Cu-target, although 5.6 GeV is required for the reaction $pp \to ppp\bar{p}$. The extra energy is supplied by the Fermi motion $\underline{q}$ of the nucleons inside the target nucleus, contributing approximately an amount $(2\ p_o \cdot q)$ to the center of mass energy squared $\underline{s}$ available in the collision. A Fermi momentum $q = 0.5$ GeV/c is sufficient to produce $\bar{p}$'s on Cu-nuclei at half the beam momentum required to reach threshold in a pp interaction. The $\bar{p}$-experiments at Berkeley demonstrated that Fermi momenta up to 0.65 GeV/c are available in heavy nuclei. On purely kinematic grounds one would conclude that with the Fermilab Energy Doubler it is possible in this way to produce at threshold masses as large as 60 GeV/c^2.

The mass range (30-60) GeV/c^2 is very tantalizing for physics. The charged weak intermediate boson W^+ could be as light as 55 GeV/c^2 in conventional[2] (and lighter in unconventional[3]) models which unify the weak and electromagnetic interactions. The t-quark is expected[4] to have a mass ~ 15-30 GeV/c^2, possibly putting it out of reach of the new generation e^+e^- machines.

The kinematic similarity between $\bar{p}$ production below threshold at the Berkeley Bevatron or the Princeton-Penn Accelerator and W or t quark production with Fermilab's Energy Doubler would only guarantee detection provided that production yield and detection signature were similar. This is of course not expected to be the case; we address these questions next.

I. NEW PARTICLE PRODUCTION CROSS-SECTIONS

We do not know a priori the dynamics of new particle production near threshold at high energy. According to quantum chromodynamics, the production of the weak boson, heavy flavor bound states, and pairs of new quarks can proceed via fusion of a quark and antiquark.[5] Gluon-induced production mechanisms are negligible near threshold. We will calculate the production cross-section in two cases:

1) the Drell-Yan mechanism: $q + \bar{q} \to \gamma \to X$;

2) a phase space calculation with no explicit dynamics.

<u>Drell-Yan mechanism</u>

The production cross section at Feynman $x_F = 0$ is given by

$$\sigma \equiv x_o \frac{d\sigma}{dx_F} = g^2 \frac{1}{3} x^2 \bar{q}(x)\ q(x) \qquad (1)$$

In Eq. 1 summation over allowed types of quarks is understood, $q(x)$ and $\bar{q}(x)$ describe the fractional momentum (x) distributions of quarks and antiquarks inside the initial nucleons and

$$x = \frac{M}{\sqrt{s}} \quad \text{or} \quad 1-x = \frac{Q}{\sqrt{s}}, \tag{2}$$

where Q is the available energy for producing a state of mass M.

The crucial observation is that $\sigma \sim u(x)\, s(x)$ in the case of pp collisions while $\sigma \sim u^2(x)$ for $\bar{p}p$ or πp collisions; $u(x)$ and $s(x)$ are the x distributions for valence and sea quarks, respectively. Typically

$$\begin{aligned} u_p(x) &= 1.79\ (1 + 2.3x)\ (1 - x)^3/\sqrt{x} \\ u_\pi(x) &= 0.75\ (1 - x)/\sqrt{x} \\ s(x) &= 0.44\ (1 - x)^{10}/x \end{aligned} \tag{3}$$

The production cross-sections in pp, $\bar{p}p$, and π^+p collisions are then

$$\begin{aligned} \sigma_{pp} &\propto (1 - x)^{13} \\ \sigma_{\bar{p}p} &\propto (1 - x)^{6} \\ \sigma_{\pi p} &\propto (1 - x)^{4} \end{aligned}$$

$(1 - x)$ is the Q-value of the production process. Because we are considering particle production near threshold, there is a strong enhancement ($\underline{\sim Q^7}$) by using valence rather than sea quarks (see Fig. 2).

In an experiment using a heavy nuclear target, two modifications of Eqs. 1 and 2 appear:

(i) the cross section σ is enhanced by a Factor A^α where A is the number of nucleons in the target element. Guided[6] by data on ψ-production and on the production of massive lepton pairs in hadron collisions, we choose $\alpha = 1$.

(ii) The available energy s^* is different from $s = 2m\,p_o$, due to the Fermi momentum q the nucleons in the target:

$$s^*(\vec{q}) = 2m^2 + 2E_o(q^2 + m^2)^{1/2} - 2\vec{p}_o\cdot\vec{q} \qquad (4)$$

The calculation of the nuclear cross sections is now straightforward; the procedure is described in detail in Ref. 7. We start by unfolding the $\bar{p}$-data to deduce the momentum distribution of the nucleons inside heavy nuclei (see Fig. 1). As is well-known, this leads to a power-law q^2 distribution of the Hulthén type whose parameters are determined by the $\bar{p}$-data. This phenomenological distribution is subsequently used to calculate the cross-section for producing a new particle of mass M on a U target. Tables I. and II. show the resulting cross sections for M = 45, 55 GeV. Production by $\bar{p}$ and π beams is enhanced a factor $\gtrsim 10^5$ relative to production by protons.

Phase space calculation

In calculating the available phase space near threshold, we assume that we do not know the dynamics at the production vertex. For each particle in the final state, the available phase space $\frac{d^3p}{E}$ contributes a factor $Q^{3/2}$ to the cross-section; after integration[7] one obtains

$$\sigma \propto Q^{[3n-5]/2} \qquad (5)$$

where n is the number of particles in the final state. Charge and baryon number conservation require that at least 3 particles accompany a W^+ produced in a proton interaction (e.g., $pp \to ppW^+\pi^-$), yielding $n \gtrsim 4$. These constraints are less stringent in $\bar{p}$ or π^+ interactions, where $n \gtrsim 2$; this corresponds to a threshold enhancement factor Q^3 purely from phase space considerations. We have calculated the production cross sections assuming the behavior of Eq. 5 at all x, with normalization to the Drell-Yan cross-section when $x \to 0$. The results are shown in Table II. for W^+ production (Eq. 1). The coupling g^2 is given by CVC:

$$g^2 = \sqrt{2}\,\pi\,G \qquad (6)$$

where G is the Fermi coupling. For producing a $t\bar{t}$ pair the effective coupling constant is expected to be somewhat larger.[9] Short of coherent effects, the phase space calculation represents the maximum cross section one can expect using Fermi motion, whereas the Drell-Yan model almost certainly underestimates the nuclear effects.

Cross section estimates for the production of "topsilon" $T(t\bar{t})$—the bound state of the charge 2/3 partner of the b-quark—have also been made.[9] They correspond to an effective coupling g^2 which is about a factor 4 smaller than the weak coupling of Eq. 6 for $m_t = 30$ GeV. This coupling is, however, enhanced by a factor 10 for $m_t = 15$ GeV. These estimates are obtained by extrapolating existing data on the hadroproduction of vector mesons.[10] Expected yields on a uranium target are shown in Table III. and Fig. 2. Figure 2 exhibits the mass dependence of the cross-section per nucleus for $\bar{p}$-uranium interactions using alternatively the Drell-Yan and phase space calculations. The leptonic branching fraction is not sensitive to the mass and is expected[9] to be 10%.

We applied the phase space calculation to the $\bar{p}$ production data ($Q^{3.5}$) of Dorfan et al., after normalizing the input pp cross-section at energies far above threshold. The agreement is impressive (see Fig. 1). We also explored subthreshold production of ψ's Υ's etc., as well as the use of lower energy beams. We will report these results elsewhere.

We summarize the conclusions based on these calculations as follows:

- Fermi-motion effects are enhanced by 10^4 - 10^{12} by using $\bar{p}$, π^+ beams,
- the smaller the ratio one gains, the larger the absolute yield becomes!
- the attractive kinematics of an "anti-quark" beam and Fermi motion also enhance the cross-sections for continuum single leptons, di-leptons, and photons.

It has been suggested that the A dependence (A^α) could increase near threshold because of coherent effects, and would significantly enhance the cross-section. We will not speculate on this aspect of nuclear enhancements, but note that the estimates of Ref. 11 are in line with our phase space calculations.

II. HIGH ENERGY BEAMS FOR "$\bar{q}$ U SCATTERING"

We describe several possibilities for exploiting the process described above, and evaluate in each case the effective nuclear luminosity.

$\bar{P}$-heavy nucleus collisions

Fermilab and CERN are each developing a system to cool and accumulate antiprotons produced from p-nucleus collisions.[12]

The system at Fermilab is shown schematically in Fig. 3. $\bar{p}$'s are produced by 80 GeV protons on a tungsten target. The $\bar{p}$'s near ($x = 0$, $p_\perp = 0$) are injected into the Booster accelerator and decelerated to 200 MeV energy. They are then transferred to a storage ring where the beam phase space is cooled by electron cooling, and accumulated in a dense stack. The design accumulation rate is $\dot{N}_{\bar{p}} = 10^{10}$/hour.[13]

This $\bar{p}$ source is expected to be operating when the Energy Doubler first circulates beam. It will then be possible to inject these antiprotons into the Main Ring, circulating in the reverse direction to normal proton operation. There the $\bar{p}$'s would be accelerated, transferred to the Energy Doubler, and accelerated to 1 TeV. Since they are traveling opposite to the usual proton orbits, extraction to the existing beam lines is precluded.[14] A fixed target experiment can thus only be done by injecting a heavy nuclear target into the beam <u>inside</u> the Energy Doubler. This technique has been used successfully on the Main Ring at the Internal Target Facility. Two possibilities suggest themselves: 1) a rotating wire target, in which ~ 2μm wires of W_{184} or U_{238} are spinning rapidly through the beam; and 2) a Hg_{200} vapor jet, in which an ~ 0.1 - 1 Torr jet of mercury vapor passes through the beam and is then condensed on baffle plates.

The utility of these techniques depends upon the balance between nuclear collisions and beam growth due to multiple scattering from the electrons of the target. The nuclear collision rate is $R = L\,\sigma_n$, where L is the luminosity for nuclear interactions, and $\sigma_n \approx \sigma_{tot}\,A^{2/3}$ is the total cross-section per nucleus.

$$L = fN_{\bar{p}}n_n\ell,$$

where $f = 4.7 \times 10^4\ \mathrm{sec}^{-1}$ is the revolution frequency,

$n_n[\mathrm{cm}^{-3}]$ = number density of heavy nuclei,

$\ell[\mathrm{cm}]$ = target length.

For A = 200, $\sigma_{tot} \sim 40$ mb, this corresponds to

$$R = 6 \times 10^{-20}\ N_{\bar{p}}n_n\ell. \tag{7}$$

Guignard[15] has calculated the rate of beam growth due to multiple small-angle Coulomb scattering:

$$\frac{1}{T} = \frac{1}{\sigma}\frac{d\sigma}{dt} = k\ \frac{\beta^* n_n Z^2}{p\ \varepsilon_o}\ \frac{\ell}{C}$$

where $\beta^*[\mathrm{m}]$ = local betatron function of the storage ring lattice,

$p = 1000$ GeV is the $\bar{p}$ beam momentum,

and $\varepsilon_o \approx 20\pi\ 10^{-6}$ m is the (invariant) initial beam emittance,

$k = 1.8 \times 10^{-19}\ \mathrm{cm}^3\ \mathrm{GeV\ sec}^{-1}$.

For Z = 80, this corresponds to

$$\frac{1}{T} = 3 \times 10^{-20}\ \beta^*\ n_n\ell. \tag{8}$$

The "efficiency" of targeting antiprotons is thus the fraction $\varepsilon = R/(R + N_{\bar{p}}/T) = 1/(1 + \beta^*/2m)$. A local $\beta^* \lesssim 2.5$ m is already envisioned in at least one long straight section in the Energy Doubler, to accommodate $\bar{p}p$ colliding beams. This corresponds to $\varepsilon \sim 1/2$: roughly half of all $\bar{p}$ s actually produce nuclear collisions in the target.

The useful luminosity is thus

$$L = \varepsilon\ \dot{N}_{\bar{p}}/\sigma_n = 8 \times 10^{29}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$$

One event per hour would correspond to a cross-section x branching fraction $\sigma \cdot B = 3 \times 10^{-34}$ cm^2/nucleus.

Pion-heavy nucleus collisions:

Fermilab is developing two high intensity pion beams for use with the Energy Doubler. The more intense one is expected to produce $\sim 2 \times 10^9$ π^+(0.9 TeV) per 10^{13} targeted protons (1 TeV). Assuming $\sim 10^{13}$ targeted protons in each one-minute cycle, the pion target rate is $\dot{N}_{\pi^+} = 3.3 \times 10^7$ sec^{-1}, and a luminosity $L = \dot{N}_{\pi^+}/(2\sigma_n/3) = 3.6 \times 10^{31}$ cm^{-2} sec^{-1}.
One event per hour would correspond to $\sigma \cdot B = 8 \times 10^{-36}$ cm^2/nucleus.

Proton-heavy nucleus collisions:

Lederman et al.[16] have studied the process $p + Pt \to \mu^+\mu^- X$ both in continum and in the Υ resonance. The useful proton intensity was limited by backgrounds to $N_p \sim 5 \times 10^{11}$p/1 sec spill. Assuming a 10 second spill for the Energy Doubler, we obtain $\dot{N}_p = 8.3 \times 10^{10}$ sec^{-1}, $L = 6 \times 10^{34}$ cm^{-2} sec^{-1}. One event per hour would correspond to $\sigma \cdot B = 5 \times 10^{-39}$ cm^2/nucleus.

III. CONSEQUENCES FOR EXPERIMENTS

The above calculations span the range of expectations (neglecting coherent effects) for new particle production near threshold. To illustrate the consequences for prospective experiments we consider two cases from Table III.

1) Drell-Yan mechanism: production of a new vector meson with mass $M_T = 30$ GeV/c^2, branching fraction $B = 0.1$:

$$\begin{aligned} 1000 \text{ GeV } \bar{p} + U &- 20 \text{ events/hour} \\ 900 \text{ GeV } \pi^+ + U &- 480 \text{ events/hour} \\ 1000 \text{ GeV } p + U &- 1280 \text{ events/hour} \end{aligned} \tag{9}$$

2) <u>Phase space calculation</u>: production of a new vector meson with mass $M_T = 56$ GeV/c^2, branching fraction $B = 0.1$:

$$
\begin{aligned}
&1000\text{ GeV } \bar{p} + U - 2 \text{ events/hour}\\
&900\text{ GeV } \pi^{+} + U - 0.3 \text{ events/hour}\\
&1000\text{ GeV } p + U - 0.7 \text{ events/hour}
\end{aligned}
\qquad (10)
$$

It is thus possible to produce new particles in the mass range (30-60) GeV/c^2, depending on which production mechanism prevails near threshold. To compare possible experiments using $\bar{p}$, π^+, and p beams, it is essential to examine the backgrounds present for di-lepton decay signatures. In this respect $\bar{p}$ and π^+ beams exhibit an enormous advantage over p beams: the production cross-section is greater by a factor ~ 10^3 - 10^5, while one expects background cross-sections to be comparable. This advantage can be useful in two ways. First, the signal/background improvement further extends the useful mass range. Second, the much smaller total interaction rate ($\dot{N}_{\bar{p}}$, $\dot{N}_{\pi^+} << \dot{N}_p$) may be compatible with experiments to detect e^+e^- decays, as well as the $\mu^+\mu^-$ decays sought in high-rate proton experiments.

<u>Experimental di-lepton mass resolution</u>

We calculate the approximate mass resolution of the experimental design of Fig. 4, for $\mu^+\mu^-$ and e^+e^- decay modes. We constrain the detector to a total length $L_1 + L_2 + L_3$ ~ 25 m, in order to accommodate placement in a long straight section of the Energy Doubler lattice. This constraint applies only for the $\bar{p}$ case, and could be extended for π^+ and p beams.

The decay mass is given by

$$M^2 \simeq 2\, p_1 p_2\, (1-\cos\theta) \simeq p_1 p_2\, \theta^2$$

In terms of the measured transverse positions x_1, x_2, x_3, the angles and momenta of each lepton are defined by

$$\theta_i = (x_1 - x_b)/L_1 \qquad \theta_f = (x_3 - x_2)/L_3$$

$$\theta_b = \theta_f - \theta_i \qquad p = .3BL_2/\theta_b$$

The angle and momentum resolution are defined by the experimental position resolution $\delta x_c \sim 0.2$ mm for chambers and $\delta x_b \sim 0.2$ mm for the beam:

$$\delta\theta_i = \sqrt{2}\, \delta x/L_1$$

$$\delta p = \sqrt{2}\, p^2 \delta\theta_i/.3BL_2$$

Choosing $BL_2 = 5$Tm, $L_1 = L_3 = 10$ m, we obtain

$$\delta\theta_i = 28\ \mu\text{rad},$$
$$\delta p = 2.6 \times 10^{-5}\, p^2$$

For most decays $p_1 \simeq p_2 \simeq p_o/2$, $\quad \theta = \theta_{i1} + \theta_{i2} \simeq 2M/p_o$.
The resulting decay mass resolution is given by

$$\delta M^2 = p_1 p_2\, \delta\theta^2 + \frac{1}{4}\left(\frac{p_1}{p_2} + \frac{p_2}{p_1}\right) \theta^2\, \delta p^2$$

$$\simeq \frac{1}{4} p_o^2\, \delta\theta^2 + 2\, \frac{M^2}{p_o^2}\, \delta p^2 = 8.5 \times 10^{-11}\, M^2\, p_o^2$$

$$\delta M/M = 9 \times 10^{-6}\, p_o$$

For p_o = 1 TeV/c, the mass resolution is $\underline{\delta M/M = 1\%}$ $(\mu^+\mu^-)$.

For e^+e^- final states, the energy of each electron is best measured using shower calorimetry. The energy resolution is typically $\delta E/E = 10\%/\sqrt{E}$. The decay mass resolution is then $\delta M/M \simeq 10\%/\sqrt{p_o}$. For p_o = 1000 GeV/c, this yields $\underline{\delta M/M = .3\%}$ (e^+e^-). The comparison of momentum (from the spectrometer) and energy (from shower calorimetry) for each electron facilitates rejection of backgrounds from pion interactions and high energy photons.

Narrow mass resolution would be useful for several reasons:

1) Rejection of continuum background;
2) For a vector meson, it would be possible to resolve the associated spectroscopy;
3) For a W, it would be possible to measure the decay width.

ACKNOWLEDGEMENT

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13. An improved collection system, now being designed, would increase the accumulation rate to 2 x 10^{11}/hour.

14. To circulate $\bar{p}$'s in the same sense as protons would require reversing both Main Ring and Energy Doubler power supplies; that is a costly modification, and we do not consider it here.

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Table I.

Drell-Yan Production of a W^+

P_o (GeV/c)	Mass (GeV/c^2)	pp	$\bar{p}p$	π^+p
p = 900	45	9.6×10^{-16}	1.7×10^{-9}	1.3×10^{-8}
	55	1.0×10^{-28}	1.5×10^{-16}	4.4×10^{-14}
p = 1000	45	1.8×10^{-14}	8.5×10^{-9}	4.9×10^{-8}
	55	3.1×10^{-22}	5.3×10^{-13}	2.3×10^{-11}

[units, mb/nucleus]

Table II.

p_o (GeV/c)	Mass (GeV/c^2)	Drell-Yan Threshold $\bar{p}$	Drell-Yan Threshold p	Drell-Yan Threshold $\bar{p}/p$	Phase Space Threshold $\bar{p}$	Phase Space Threshold p	Phase Space Threshold $\bar{p}/p$
p = 900	45	1.7×10^{-9}	9.6×10^{-16}	1.8×10^{6}	4.4×10^{-4}	4.5×10^{-8}	9.8×10^{4}
	55	1.5×10^{-16}	1.0×10^{-28}	1.5×10^{12}	7.8×10^{-7}	3.7×10^{-13}	2.1×10^{6}
p = 1000	45	8.5×10^{-9}	1.8×10^{-14}	4.7×10^{5}	1.4×10^{-3}	1.6×10^{-7}	8.8×10^{3}
	55	5.3×10^{-13}	3.1×10^{-22}	1.7×10^{9}	1.3×10^{-5}	1.2×10^{-10}	1.1×10^{5}

[units, mb/nucleus]

Cross-sections normalized for W^+ production.

Cross-sections for vector meson production are smaller by ~ x 4.

Table III.

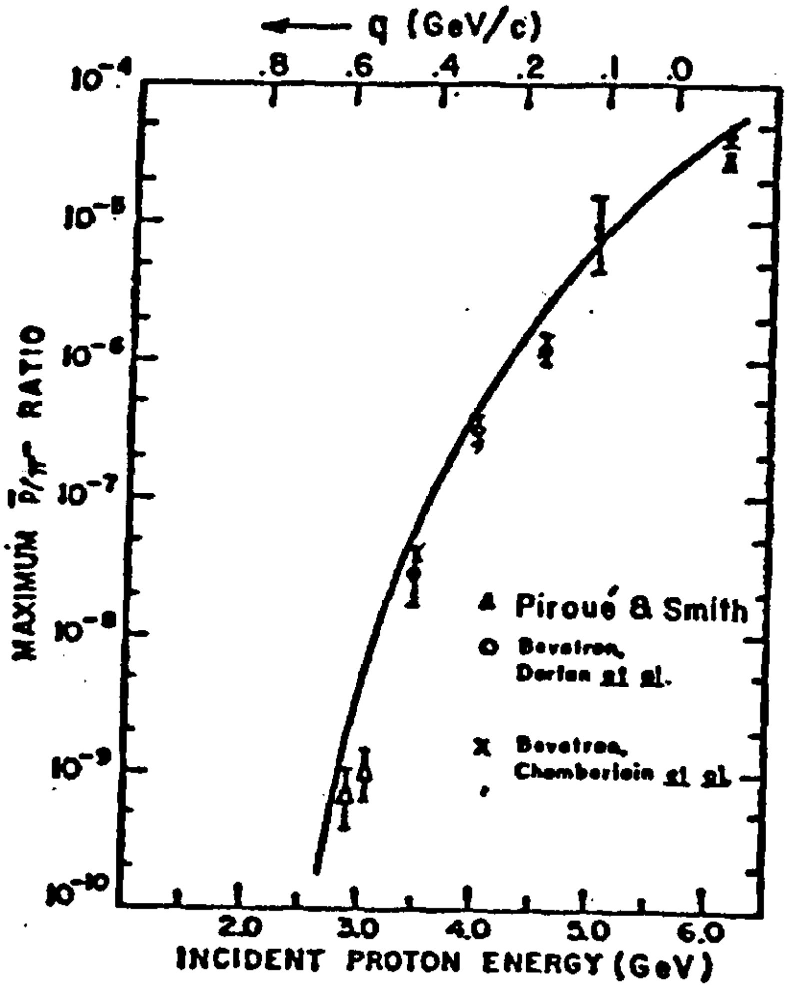
$\Upsilon(\bar{t}t)$ Production

p_o (GeV/c)	M = 30 GeV/c^2 p	p	π^+ (x=0.9)	M = 56 GeV/c^2 p	$\bar{p}$	π^+ (x=0.9)
1000	7.8×10^{-8}	9.5×10^{-5}	3.7×10^{-5}	7.8×10^{-23}	2.7×10^{-13}	1.1×10^{-14}
		3.1×10^{-2}	3.6×10^{-3}	3×10^{-11}	6.5×10^{-6}	2.5×10^{-8}
400	3.8×10^{-17}	8.5×10^{-10}	1.4×10^{-8}			
	$2. \times 10^{-8}$	6.5×10^{-4}	8×10^{-5}			

In each case, upper value is Drell-Yan mechanism, lower value is phase space calculation.

FIGURE CAPTIONS

1. $\bar{p}$ production below threshold. Data are from Ref. 1 The curve represents the phase space calculation for $pp \rightarrow pp\bar{p}p$.
2. Cross-section for producing a new vector meson using p_o = 1 TeV. Estimates are shown for a) pp (Drell-Yan); b) $\bar{p}p$ (Drell-Yan); c) $\bar{p}U$ (Drell-Yan); and d) $\bar{p}U$ (phase space). Cross-sections for a) and b) have been multiplied by A = 238 for comparison with c) and d).
3. $\bar{p}$ Source at Fermilab.
4. $\bar{p}$ Internal Target Experiment.



q (GeV/c)
.8
.6
.4
.2
.1
.0
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
MAXIMUM $\bar{p}/\pi^{-}$ RATIO
Piroué & Smith
Bevatron, Dorfan et al.
Bevatron, Chamberlain et al.
2.0
3.0
4.0
5.0
6.0
INCIDENT PROTON ENERGY (GeV)

Fig. 1

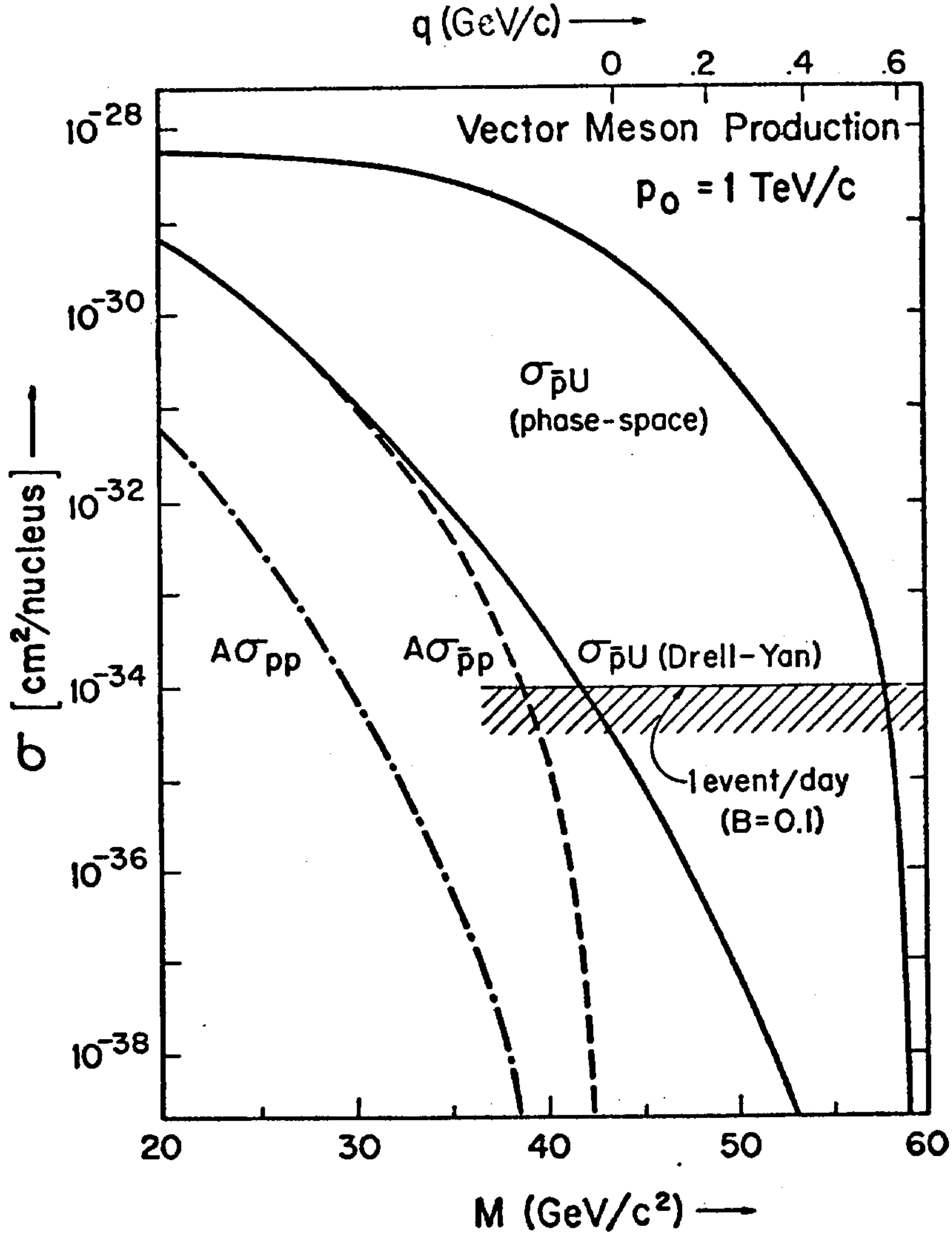
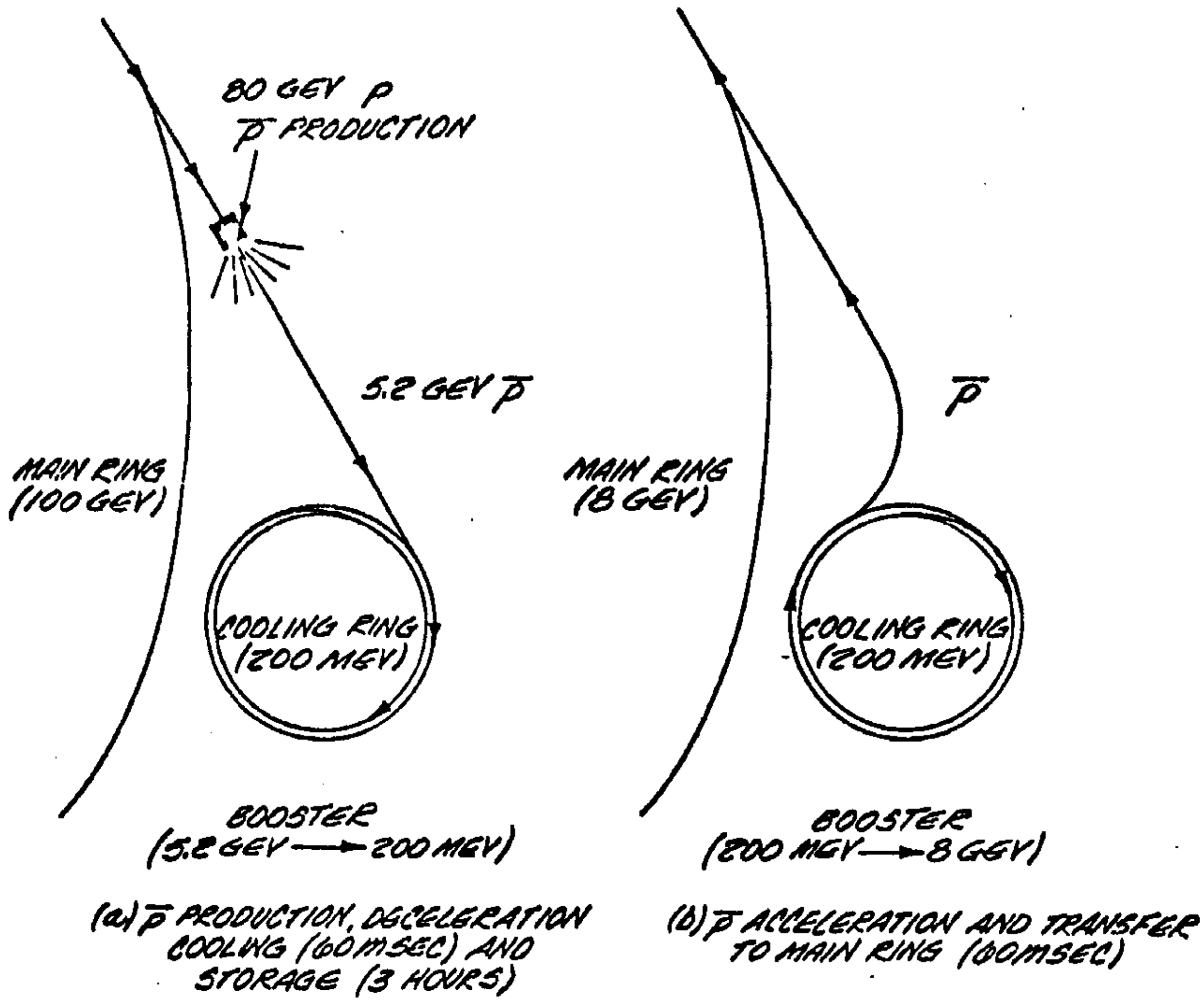
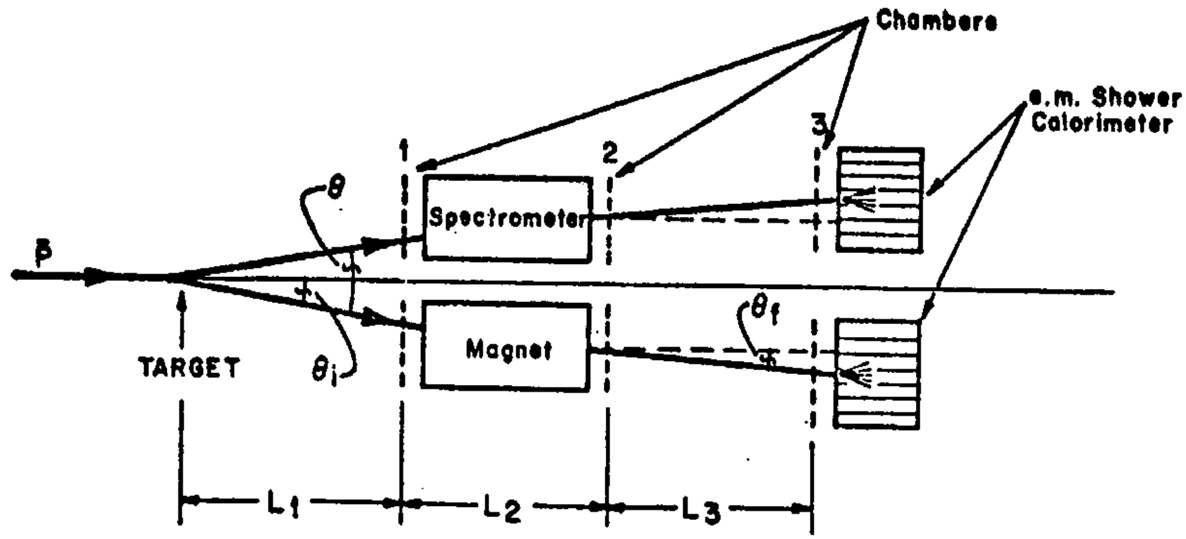

q (GeV/c) →
0
.2
.4
.6
Vector Meson Production
$p_0 = 1$ TeV/c
10^{-28}
10^{-30}
10^{-32}
10^{-34}
10^{-36}
10^{-38}
σ [cm²/nucleus] →
$\sigma_{\bar{p}U}$
(phase-space)
$A\sigma_{pp}$
$A\sigma_{\bar{p}p}$
$\sigma_{\bar{p}U}$ (Drell-Yan)
1 event/day
(B=0.1)
20
30
40
50
60
M (GeV/c²) →

Fig. 2



$\bar{P}$ SOURCE AT FERMILAB

Fig.3



$\bar{P}$ INTERNAL TARGET EXPERIMENT

Fig. 4